Elliptic lowpass audio filter design using miniature preferred value components

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Stefan (Stef to his friends) Niewiadomski is a 32-year old professional electronics engineer, mainly involved with digital circuit design. His interest in radio and electronics began in his early teens, and he obtained a BEng in 1973 and, more recently, an MSc in modern electronics. At present his main interest in electronics is circuit simulation by computer; outside electronics his interests include walking and playing snooker.

A RECENT ARTICLE in *Radio Communication* [1] introduced amateur constructors to methods of designing elliptic lowpass filters using tables of normalized component values. The final values of the capacitors and inductors are obtained by scaling the normalized values to obtain the correct frequency response and input and output impedance. Almost invariably, the values obtained do not correspond to preferred values which are easily available to amateurs.

More recently, a second article [2] indicated that specific designs could be realized using surplus 88mH inductors. However, these inductors are not well suited to modern construction techniques on printed circuit boards, and the effect of using a single preferred value component for each capacitor was not investigated.

Additionally, neither article investigated the effect of finite values of Q for the real inductors which have to be used in any application.

This article is divided into three parts:

1. An investigation into the use of preferred value capacitors and inductors using computer simulation techniques, taking a filter published in the *Radio Communication Handbook* as an example.
2. An investigation into the effect of low-Q inductors by simulation and practical tests.
3. A brief description of other factors which should be considered when assessing an audio filter for use in a radio receiver.

Computer simulation of preferred value designs

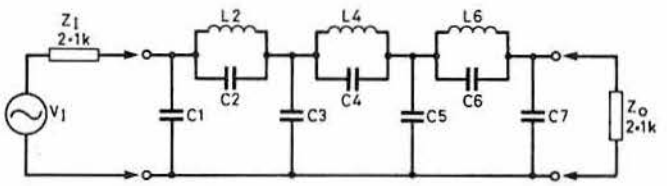
Initially a lowpass design published in the *Radio Communication Handbook* (Fig 4.67(a)), shown here in Fig 1, was simulated on an Apple 2 microcomputer using a network analysis program [3]; the first column of the table in Fig 1 lists the component values recommended in the *Handbook*. The capacitor values can be obtained by connecting several smaller values in parallel (four are suggested for C1) and the inductors must be handwound, each with several hundred turns of wire. The results are plotted in Fig 2: (a) shows the passband response, and (b) the response from 2·5 to 10kHz.

It can be seen that up to 2·5kHz the passband ripple is 0·18dB and the ultimate stopband attenuation is more than 60dB. One interesting property of such an "ideal" elliptic filter can be seen: the ripples in the passband are of equal amplitude, as are the peaks of minimum attenuation in the stopband. Books which present tables of elliptic filters tend only to give these equi-ripple designs.

The values of the capacitors and inductors of this filter were rounded to the nearest preferred value to investigate what effect this would have on the response. Some were rounded up and others down and the second column of the table in Fig 1 shows the values obtained. The modified network was simulated, and the results are also shown in Figs 2(a) and (b) for comparison with the unrounded component response.

Surprisingly, the performance of the filter has changed very little. The passband ripple has increased slightly and the ripples are no longer equal in amplitude. In the transition region and the stopband the performance is very similar to the unrounded component response. A change in the frequencies of maximum attenuation has occurred, as would be expected by the changes in the resonant frequencies of L2/C2, L4/C4 and L6/C6. The peaks of minimum attenuation in the stopband are now unequal, though the ultimate stopband attenuation still levels out at approximately 60dB.

To the ear, the performance differences of the two filters would be undetectable. These results seem to suggest that if the amateur intends to build this filter the values of the inductors (and hence the number of turns of wire on the pot cores) and the capacitors are not critical. This fact alone makes the filter easier and cheaper to construct as the sets of parallel capacitors are not required.



Component	Theoretical values	Rounded values
C1	37·26nF	39nF
C2	3·871nF	3·9nF
C3	51·87nF	56nF
C4	19·06nF	18nF
C5	46·41nF	47nF

Component	Theoretical values	Rounded values
C6	13·53nF	15nF
C7	29·85nF	27nF
L2	168·2mH	180mH
L4	124·5mH	120mH
L6	129·5mH	120mH

Fig 1. *Radio Communication Handbook* Fig 4.67(a)

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Practical components

Obviously, preferred value capacitors are easily and cheaply available to all amateurs. As far as I am aware, there is only one source of preferred value prewound inductors easily available in the UK: Toko manufacture their 10RB and 10RBH range in the E12 series of values from 1mH to 1,500mH, and these are available from Cirkit Holdings. Being only 14mm high and 10·5mm in diameter, they are ideally suited to printed circuit board mounting in compact modern equipment. The only potential drawback of these components is their relatively low Q at audio frequencies. For example, the 47mH component is quoted as having a dc resistance of 52Ω [4] and the Q at 1kHz is given by:

$$Q = \frac{2\pi fL}{R} = \frac{2\times\pi\times10^{3}\times47\times10^{-3}}{52} = 5{\cdot}68$$

Examination of a 47mH Toko inductor after removing its outer ferrite casing revealed a wire size of approximately 40swg. The Q of an inductor wound by hand on a ferrite core depends on the gauge of wire used, but would typically be much greater than the value obtained above. A theoretical explanation of the effect that finite-Q inductors have on the performance of tuned circuits is given in the 1983 *ARRL Handbook* [5]. The effects will now be investigated using simulation and practical tests.

Simulation of filters using lossy inductors

To investigate the effects of low-Q inductors, a filter was designed with the specification shown below Fig 3. A five-pole filter was found to be capable of meeting these requirements, and the circuit of this filter, with a resistor in series with each inductor to represent its finite Q, is shown in Fig 3. The component values listed in the first column of the table in Fig 3 are the theoretical values obtained. These were then rounded to the nearest preferred value. L4 has the theoretical value of 43mH, which is exactly midway between the preferred values 39mH and 47mH. In the interests of standardization, the value of 47mH was chosen.

The results of the simulations are shown in Figs 4(a) and (b). It can be seen that the theoretical values meet the filter design criteria of the Fig 3 table. The passband ripple is 1dB, the cut-off frequency is 3kHz and the stopband attenuation is 55dB. The two frequencies of high attenuation in the stopband are 4,780Hz and 7,200Hz.

Also plotted on Figs 4(a) and (b) are the results for the real, lossy inductors and rounded values. The effects of these changes are:

(a) a non-zero insertion loss at all frequencies;
(b) increased ripple in the passband;
(c) greater rounding of the passband edge;
(d) slight shifts in cut-off and high-attenuation frequencies;
(e) non-infinite attenuation at high-attenuation frequencies;
(f) stopband attenuation less than the design aim.

A practical test

To check the validity of the simulation results of Fig 4, the filter with the component values in the second column of the Fig 3 table was constructed. Siemens metallized polyester capacitors with 10 per cent tolerance and Toko 10RB inductors (five per cent tolerance) were used.

The frequency response of the filter was measured using a Hewlett Packard 3585A spectrum analyser and Bryans 25000 XY pen plotter in the configuration shown in Fig 5. The spectrum analyser has an output impedance of 50Ω, so series resistance was added to obtain the correct source impedance for the filter of 1kΩ. A 1kΩ resistor was used to terminate the filter output, and the output voltage was monitored with a 1MΩ input impedance probe. To prevent the possibility of dc flowing through the inductors, a 100μF capacitor was placed in series with the input. The Toko inductors are sensitive to saturation by dc, so steps should always be taken to prevent any dc component in their drive current.

The spectrum analyser was set to generate a frequency source from 20Hz to 10kHz while monitoring at the source frequency. The ratio of the output to input voltage (expressed in decibels) is calculated by the analyser and displayed on the screen of the instrument. Results were plotted by the pen plotter under the control of the analyser on the axes of Figs 4(a) and (b) so that they could be compared directly with the simulation results.

In the passband the experimental results compare with the simulated results of the real inductors to within approximately 1dB. In the transition region between the passband and stopband, good agreement can be seen between the theoretical values simulation, the real inductors simulation and the practical results. When the stopband region is reached, the practical results indicate an ultimate attenuation of approximately 55dB, but the first peak in minimum attenuation (at about 5·5kHz) is only 50dB. The points of very high attenuation in the stopband are not realized in the simulation

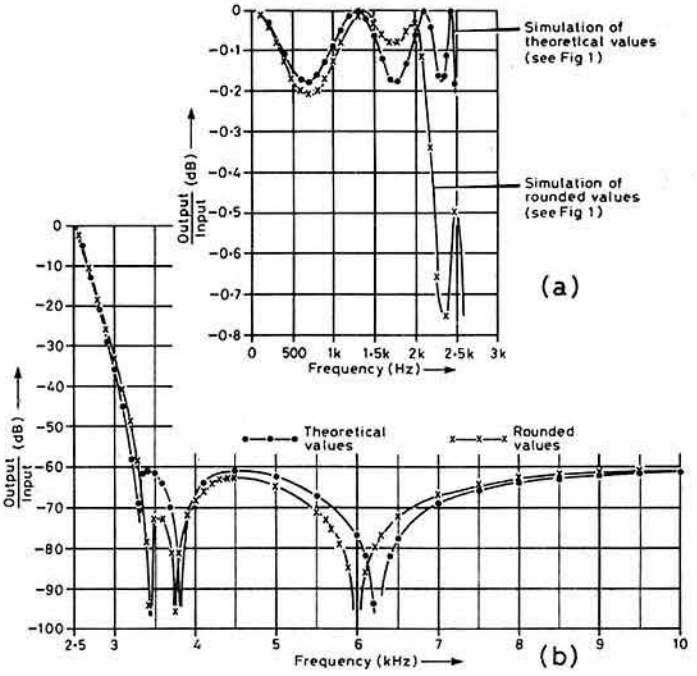


Fig 2. (a) Passband response of *Handbook* filter. (b) 2·5–10kHz response of *Handbook* filter

with real inductors and the practical results, particularly the first peak at approximately 4·5kHz.

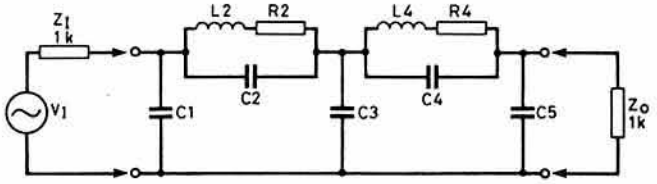
The differences between the simulation results with real inductors and the practical results are most probably due to the difference between the nominal values of the components and their actual values. At higher frequencies the model of the low-Q inductors as a pure inductor in series with a constant value resistor becomes less accurate. Skin effects and the interwinding capacitance of the inductors become more significant. Another effect is coupling between the input and the output of the filter because of imperfect layout. This effect cannot be modelled easily.

Further points for consideration in receiver design

Though not strictly within the terms of reference of this article, there are other factors which should be taken into account when assessing a filter for use in a radio receiver for speech. The two main factors which are most likely to affect the level at which the user of a receiver perceives a signal other than the filter response are:

(a) the transfer function of electrical power input to sound pressure output of the loudspeaker or headphones (assuming that the audio amplifier has a flat response—a reasonable assumption), and
(b) the variation with frequency of perceived loudness by the human ear.

The usual method of mounting a loudspeaker in a receiver's metal case



Component	Theoretical values	Rounded values
C1	0·1048μF	0·1μF
C2	9·4nF	10nF
C3	0·1336μF	0·12μF
C4	25·8nF	27nF
C5	91·9nF	0·1μF

Component	Theoretical values	Rounded values
L2	52·3mH	47mH
L4	43·0mH	47mH
R2	0Ω	52Ω
R4	0Ω	52Ω

Input impedance 1kΩ
Output impedance 1kΩ
Maximum pass-band ripple 1dB
Cut-off frequency 3kHz
Minimum stop-band attenuation 55dB
Frequency of high attenuation ..... 4·5kHz

Fig 3. Five-pole filter to specification shown

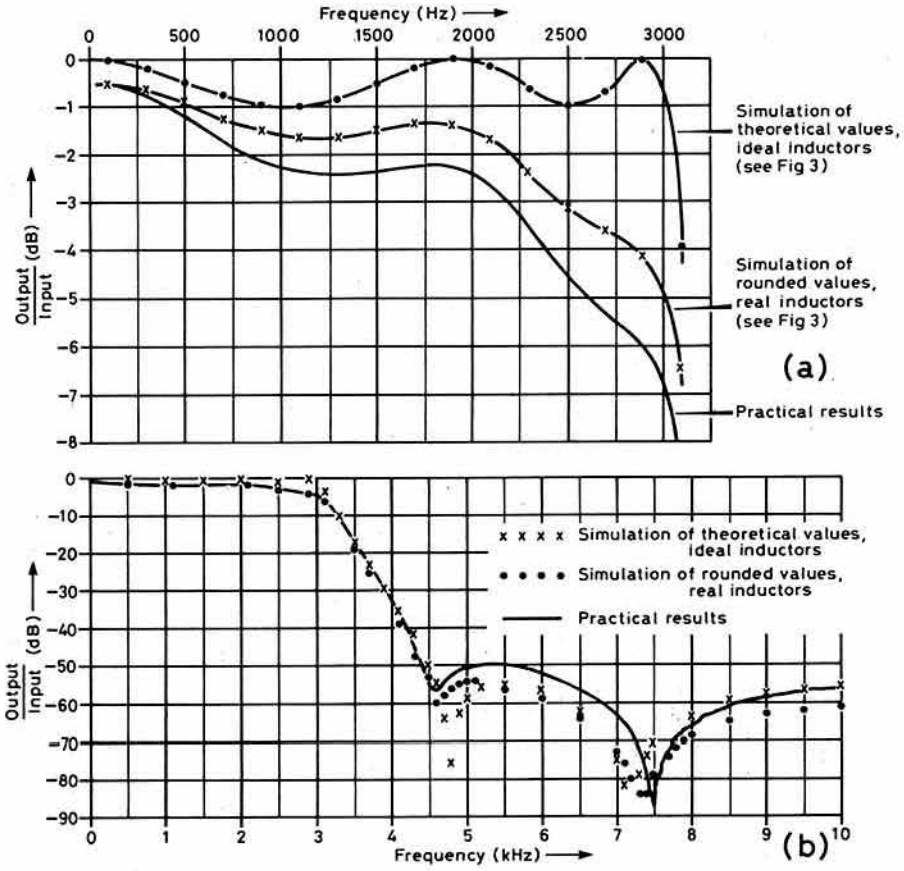


Fig 4. (a) Passband response of Fig 3 filter, including practical results. (b) 0–10kHz response of Fig 3 filter including practical results

is far from ideal. Typically a 4in loudspeaker in free air exhibits a 9dB ripple from 1 to 3kHz in its sound pressure output [6]. In a metal case with no baffle the resonances produced are too complex to predict analytically.

Experiments performed to measure the thresholds of audibility for pure tones [7] indicate that the human ear exhibits approximately 8dB variation in the range 1 to 3kHz, being more sensitive at middle frequencies. This variation increases as the age of the subject increases.

These two factors tend to negate efforts to minimize the passband ripple of the audio filter. In this context it is thought that passband ripples of up to 3dB are insignificant for speech communication.

Conclusions

Computer simulation studies and laboratory measurements have been presented which show that elliptic lowpass audio filters can be constructed using preferred value inductors and capacitors. While the performance is not as good as can be achieved using precision inductors and capacitors, it is still acceptable for most applications. The use of preferred value inductors in particular will lead to a considerable reduction in cost and volume when compared with the use of handwound ferrite pot-cores. The only range of such inductors easily available to the amateur to my knowledge is quite acceptable despite the lossy nature of these components.

Though not described in this article I have found that highpass and bandpass audio filters of all types can also be constructed with great success using these miniature preferred-value components.

When choosing an audio filter to follow the detector stage in a receiver, other factors may well make the passband ripple of the filter not as important as might be first thought.

Radio amateurs should therefore consider trying this alternative approach to filter construction, and only if this fails to give the desired performance should the more expensive alternative be used.

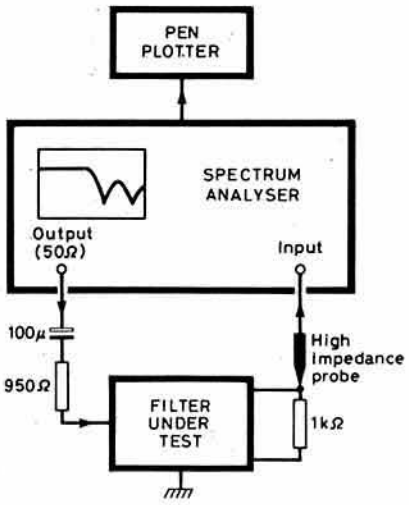


Fig 5. Test set-up to measure filter response

References

[1] "An introduction to elliptic filters for the radio amateur", J. Wilkinson, G4HGT. *Rad Com* February 1983.

[2] "Simplified elliptic lowpass filter construction using surplus 88mH inductors", E. E. Wetherhold, W3NQN. *Rad Com* April 1983.

[3] "Basic program performs circuit analysis", R. Steincross. *EDN* 1 September 1982.

[4] *Ambit components catalogue*, Summer 1983.

[5] 1983 *ARRL Radio Amateur's Handbook*, pp2-34 to 2-36.

[6] *Mullard technical handbook*, book 3, part 5, AD4090/X series loudspeakers. August 1978.

[7] *Telecommunication by speech*, D. L. Richards. Butterworths, 1973, p83.

Other useful publications

Simplified modern filter design, Philip R. Geffe; Iliffe.

Handbook of filter synthesis, A. I. Zverev; Wiley.

Filter design and evaluation, G. E. Hansell; Van Nostrand Reinhold Company. □